A New Empirical Model of Ion and Electron Fluxes at Geosynchronous Orbit

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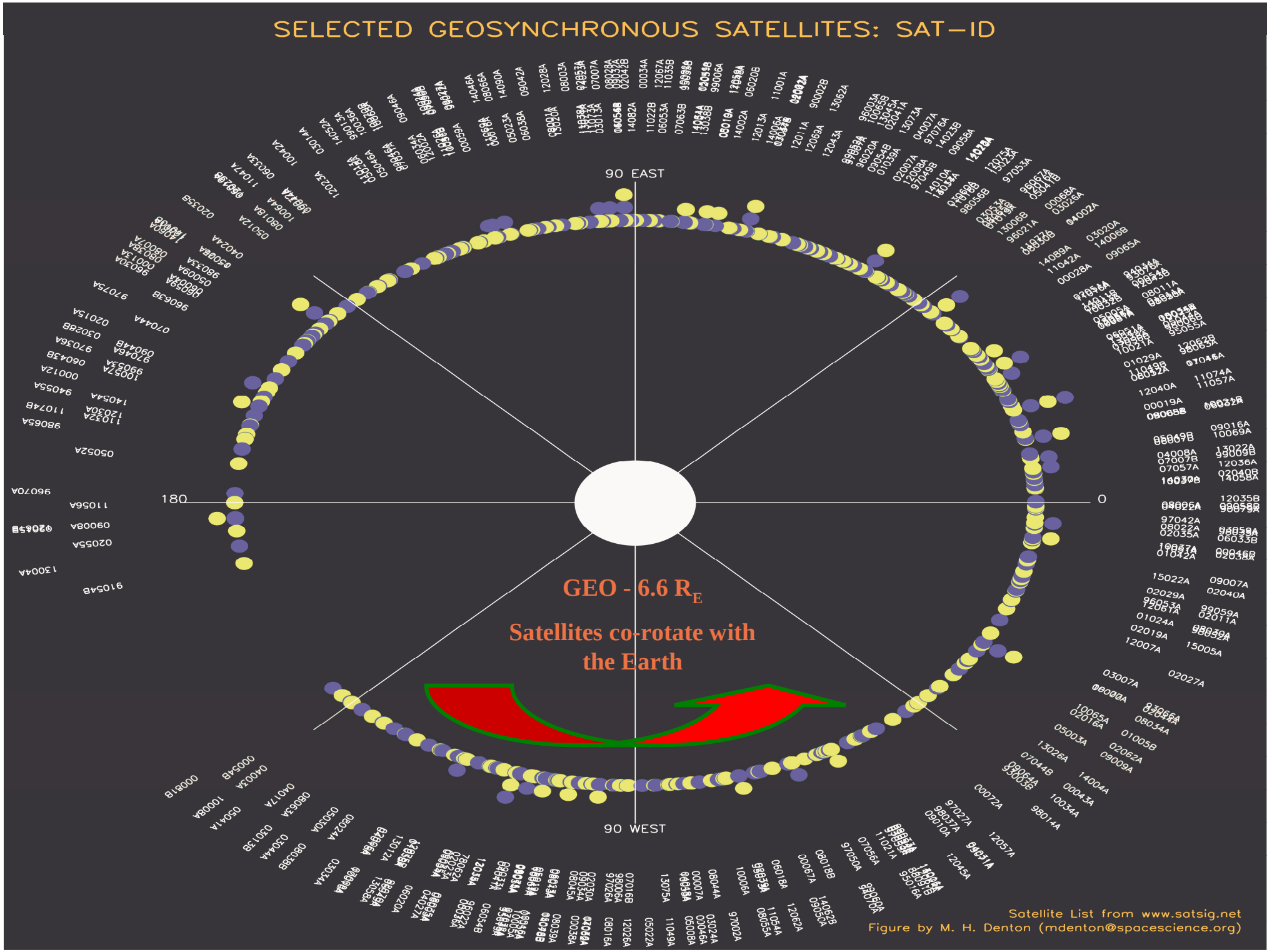
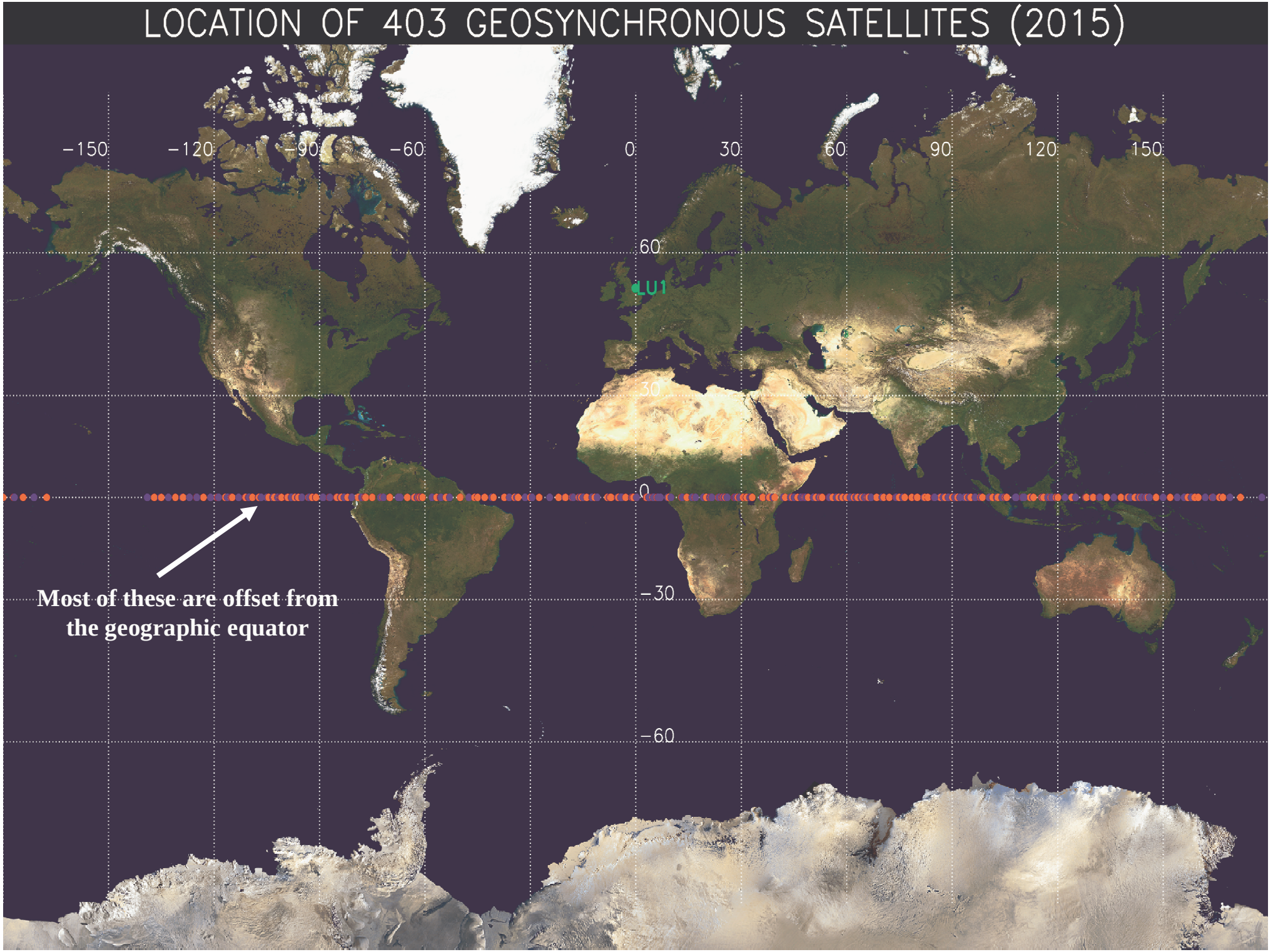

SELECTED GEOSYNCHRONOUS SATELLITES: SAT—ID
90 EAST
180
0
90 WEST
GEO - 6.6 R_E
Satellites co-rotate with the Earth
Satellite List from www.satsig.net
Figure by M. H. Denton (mdenton@spacescience.org)


LOCATION OF 403 GEOSYNCHRONOUS SATELLITES (2015)
−150
−120
−90
−60
0
30
60
90
120
150
60
30
0
−30
−60
LU1
Most of these are offset from
the geographic equator

About Geosynchronous Orbit (GEO)

WHAT IS SO SPECIAL ABOUT GEO?

- **Science**

  GEO is the boundary between the inner and the outer magnetosphere.

  Plasma enters the inner magnetosphere from the plasma sheet during periods of enhanced convection.

  Models use plasma conditions at GEO as input/boundary conditions.

- **Operations**

  Home to >400 satellites (military, scientific, industry)

  Need to specify the flux environment to design and operate robust, reliable hardware (as cheaply as possible).

  Need to predict flux in advance to prepare for harsh/dangerous conditions.

What Do We Need To Know?

The Particle Flux:

The number of particles (electrons or ions) passing through a 2D slice of space per unit of time

We want to know how this flux changes as a function of:

- **Energy usually measured in electron Volts (eV)**
- **Local Time around GEO (0-24 hours)**
- **Activity (how "active" the system is)**

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Analagous to weather forecasting.....where we need to predict rainfall as a function of day, season, geographic location, etc.

Do We Need Another Model?

<u>Robert Fitzroy</u>: Royal Navy

Captain of HMS Beagle

Suspected the links between pressure and weather could be exploited

Set up system of multiple pressure measurements on and off shore

Coined the term '*weather forecast*'

Fitzroy's primary interest was protecting naval assets

For those interested in '*space weather*' and '*orbital assets*' we need accurate environmental forecasts also.

Do We Need Another Model?

Numerous models of the flux environment at GEO already exist.

e.g.

- → **AP9/AE9/SEM [*Ginet et al.*, 2014]**
- → **IGE-2006 [*Sicard-Piet et al.*, 2008]**
- → **two-Maxwellian ATS-6 models [*Purvis et al.*, 1984]**

♣ **Models focus on spacecraft operations and operational requirements... (total dose, surface charging, internal charging).**

♦ **Some variables known to affect flux are not considered... (e.g. changes in driving by the solar wind).**

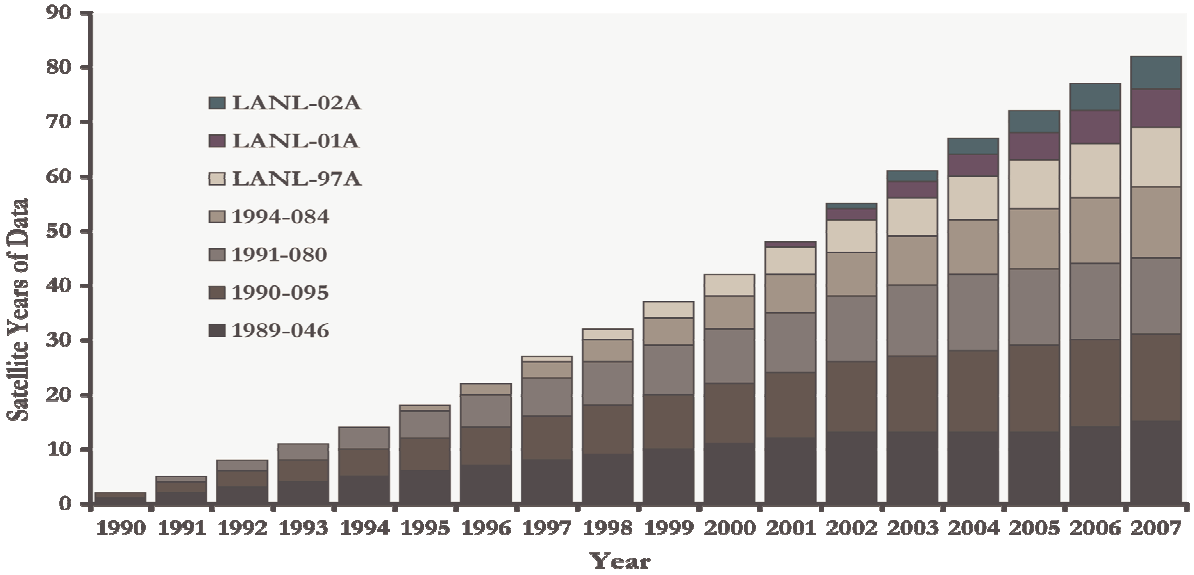
♠ **Models have limited input parameters (e.g. Kp only) and may only operate over a restricted energy range...**

♥ **Our aim is to complement, not replace, existing models...**

Do We Need Another Model?

Our aim, in designing a new model, is to utilize the large database of measurements from GEO taken over the last two solar cycles (and beyond).

Use data from Los Alamos National Laboratory (LANL) satellites, MPA instrument.

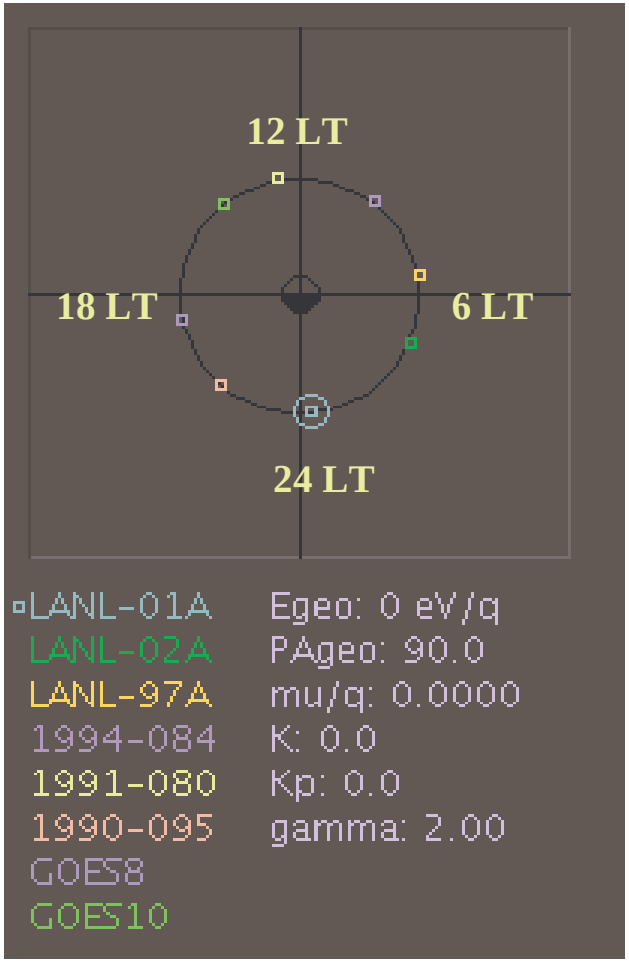


7 satellites at GEO

82 satellite-years of data

1.5 solar cycles

~1 eV to ~40 keV



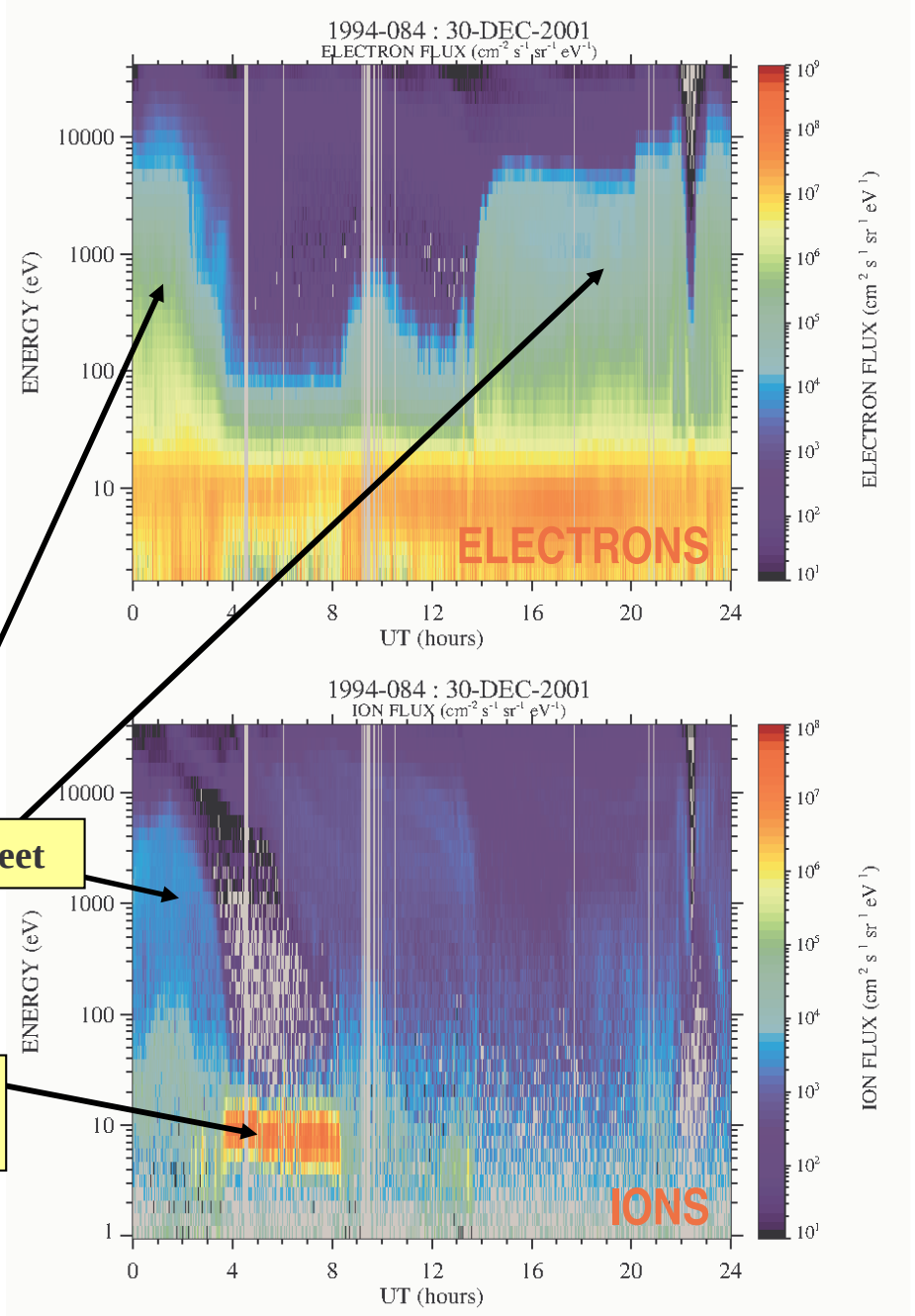
Model Description

So what data goes into the model?

ALL DATA EXCEPT:

Periods when satellites are in the magnetosheath.

Each bin must contain >5 data points. Most bins have >10^5 points.

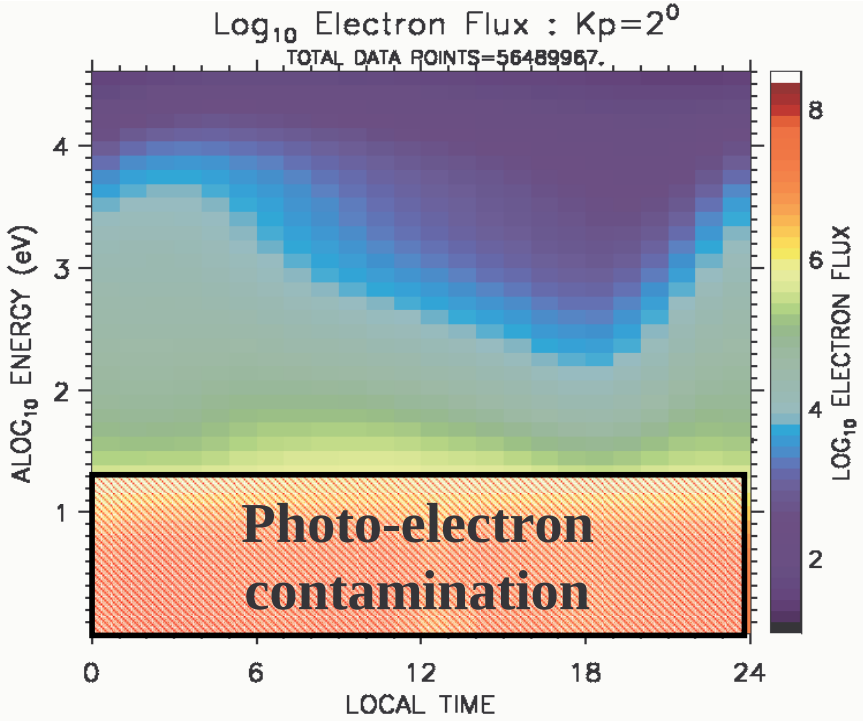


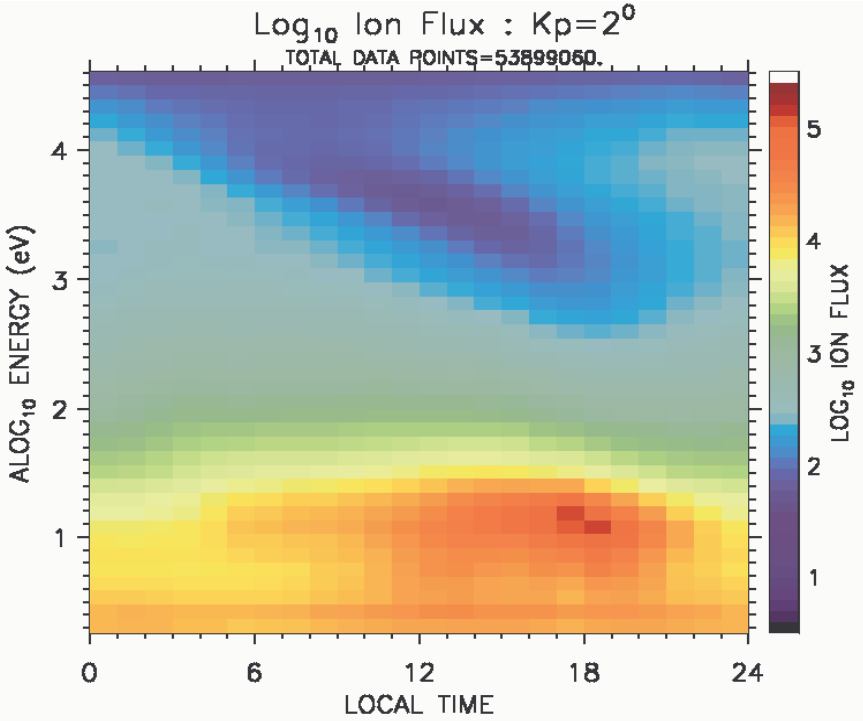
Plasma Sheet

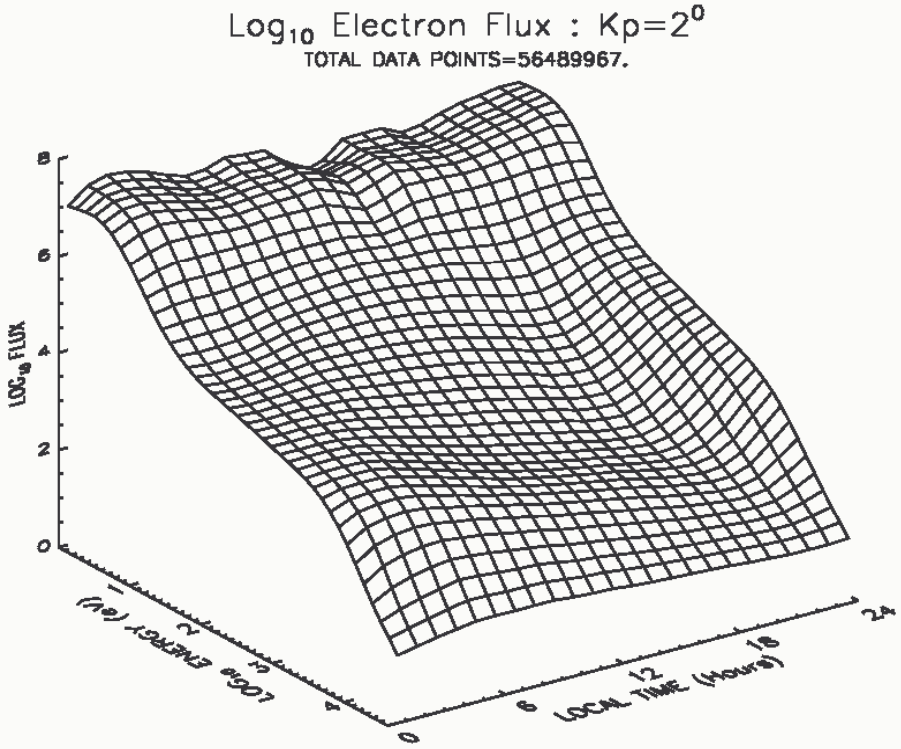
Plasmaspheric drainage plume

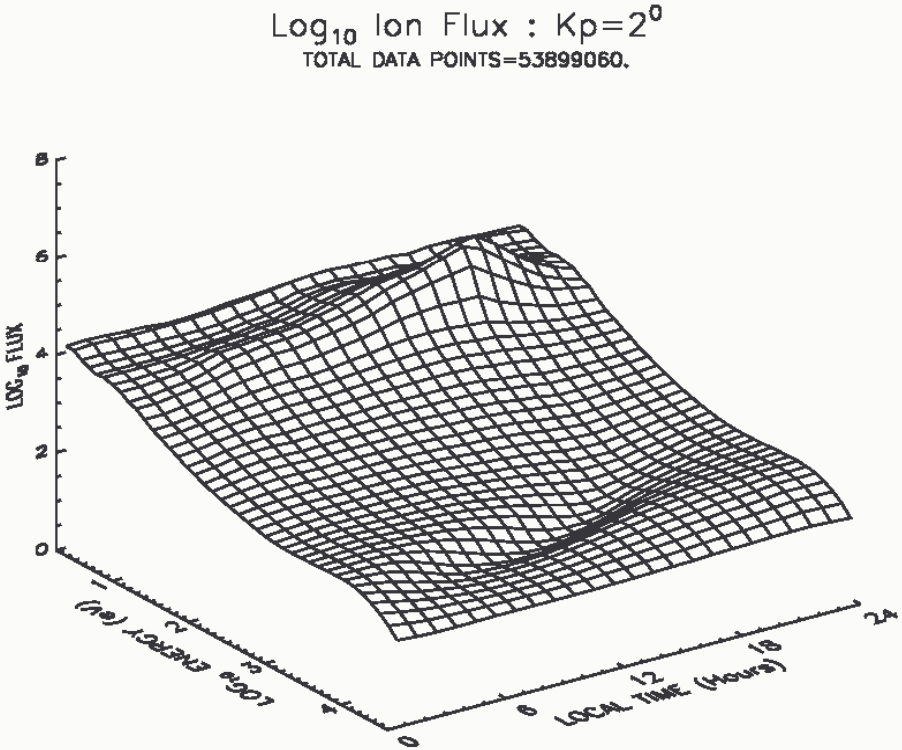
Original Model Description

- Use 82 satellite-years of LANL/MPA data
- Flux from LANL/MPAs match to ~20% [Thomsen et al., 2007]
- Bin data in a grid of 24×1 hour bins in local time and 40× energy bins (evenly spaced logarithmically) from ~1 eV to ~40 keV.
- Calculate mean, standard deviation, median, and other percentiles in each bin.
- Repeat this process for each of the 28 possible Kp values.
- Use bi-linear interpolation to calculate flux (and percentiles) at any local time and energy, for any Kp.


Log10 Electron Flux : Kp=2^0
TOTAL DATA POINTS=56489967.
ALOG10 ENERGY (eV)
LOG10 ELECTRON FLUX
LOCAL TIME
Photo-electron contamination


Log10 Ion Flux : Kp=2^0
TOTAL DATA POINTS=53899060.
ALOG10 ENERGY (eV)
LOG10 ION FLUX
LOCAL TIME


Log10 Electron Flux : Kp=2^0
TOTAL DATA POINTS=56489967.
LOG10 FLUX
LOG10 ENERGY (eV)
LOCAL TIME (Hours)


Log10 Ion Flux : Kp=2^0
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LOG10 FLUX
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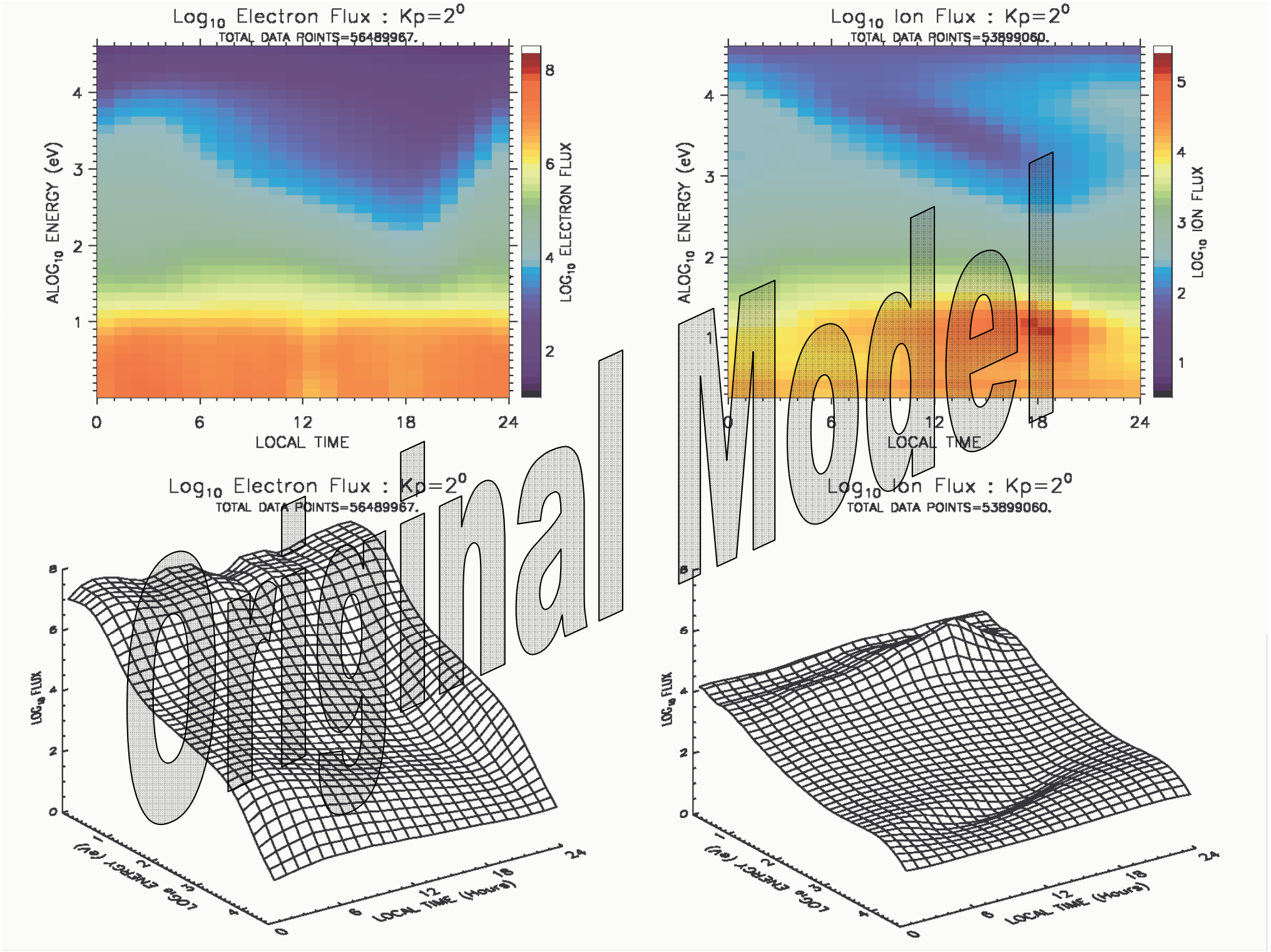
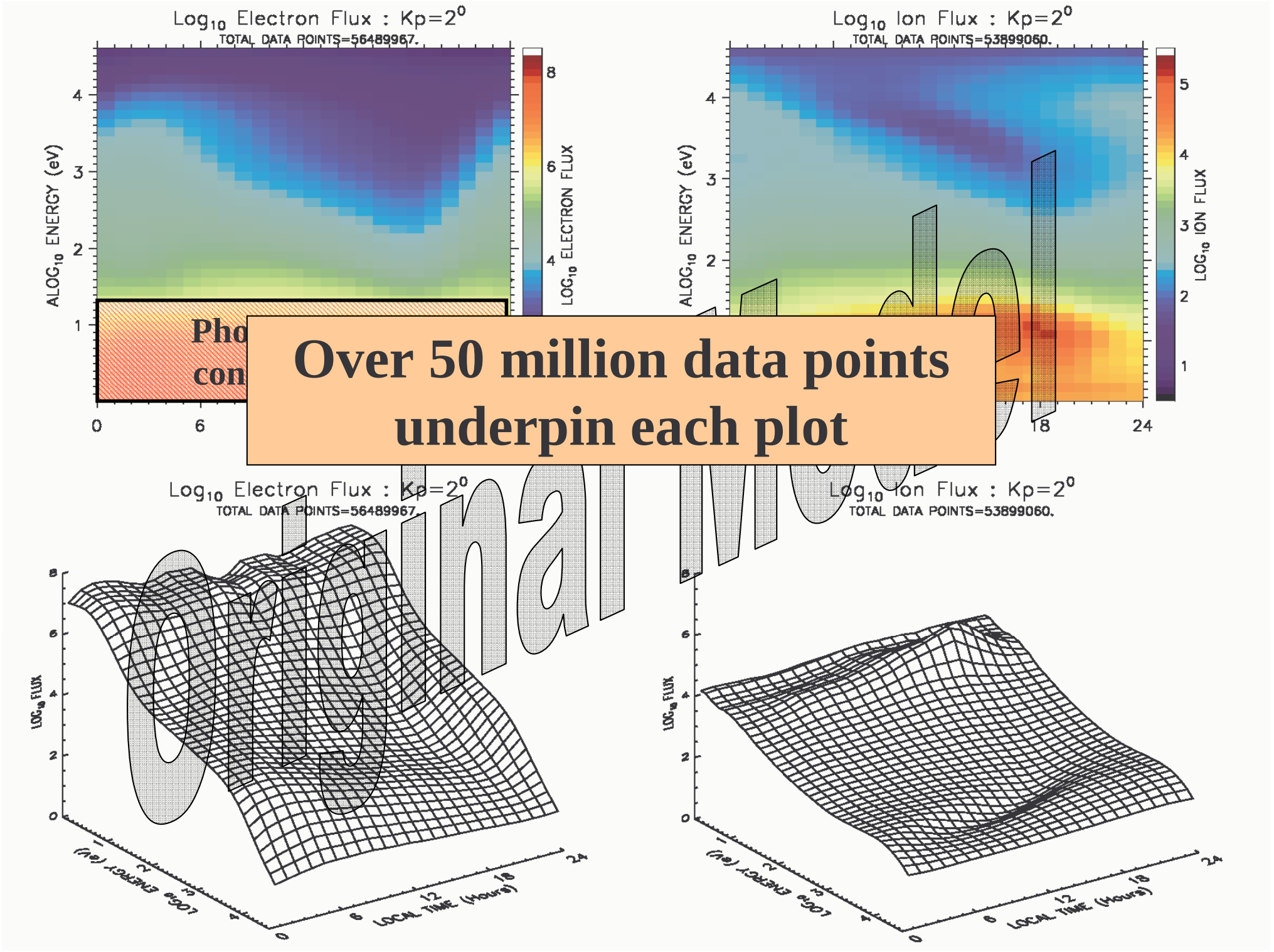
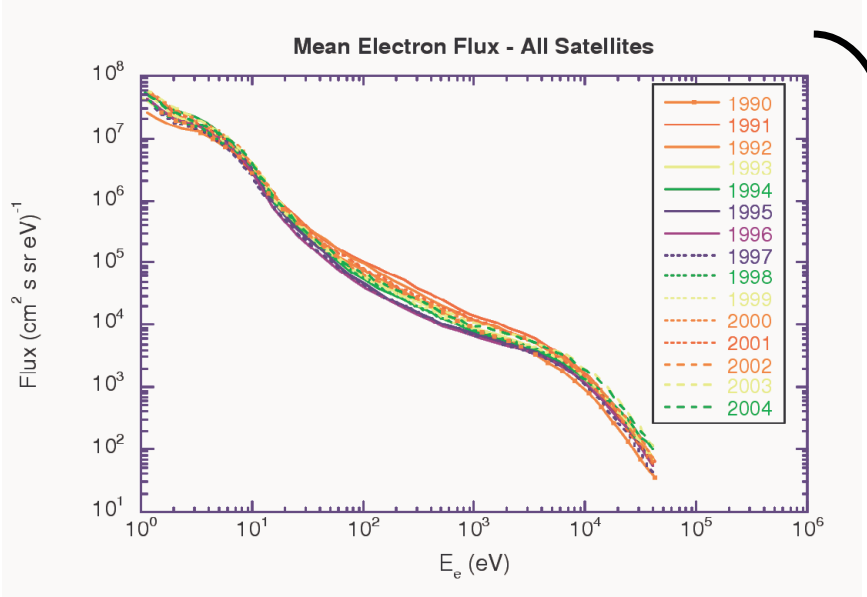
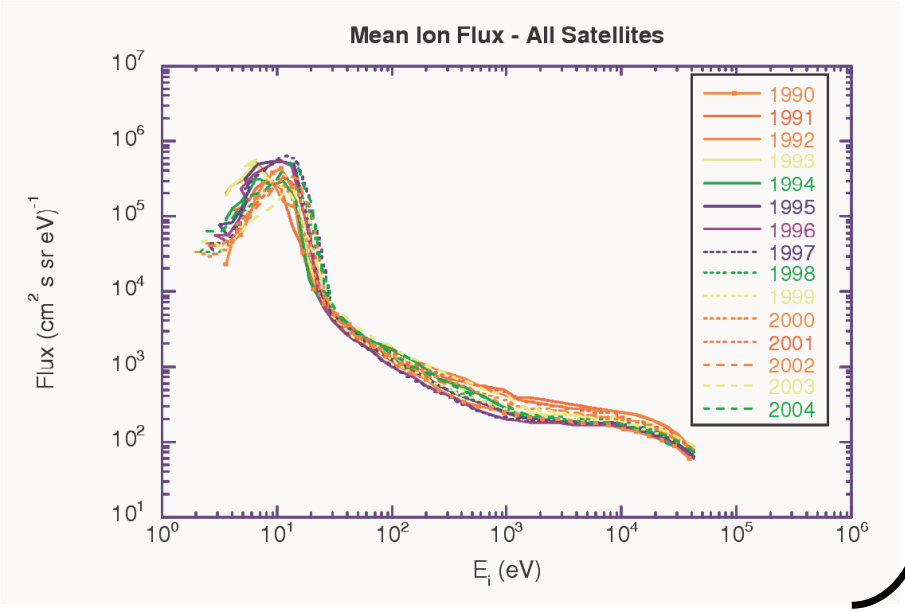
LOCAL TIME (Hours)


Log10 Electron Flux : Kp=2^0
TOTAL DATA POINTS=56489967.
ALOG10 ENERGY (eV)
LOG10 ELECTRON FLUX
LOCAL TIME
Log10 Ion Flux : Kp=2^0
TOTAL DATA POINTS=53899060.
LOG10 ION FLUX
Original
Model
LOG10 FLUX
LOG10 ENERGY (eV)
LOCAL TIME (Hours)


Log10 Electron Flux : Kp=2^0
TOTAL DATA POINTS=56489967.
ALOG10 ENERGY (eV)
LOG10 ELECTRON FLUX
Log10 Ion Flux : Kp=2^0
TOTAL DATA POINTS=53899060.
LOG10 ION FLUX
Over 50 million data points underpin each plot
LOG10 FLUX
LOCAL TIME (Hours)

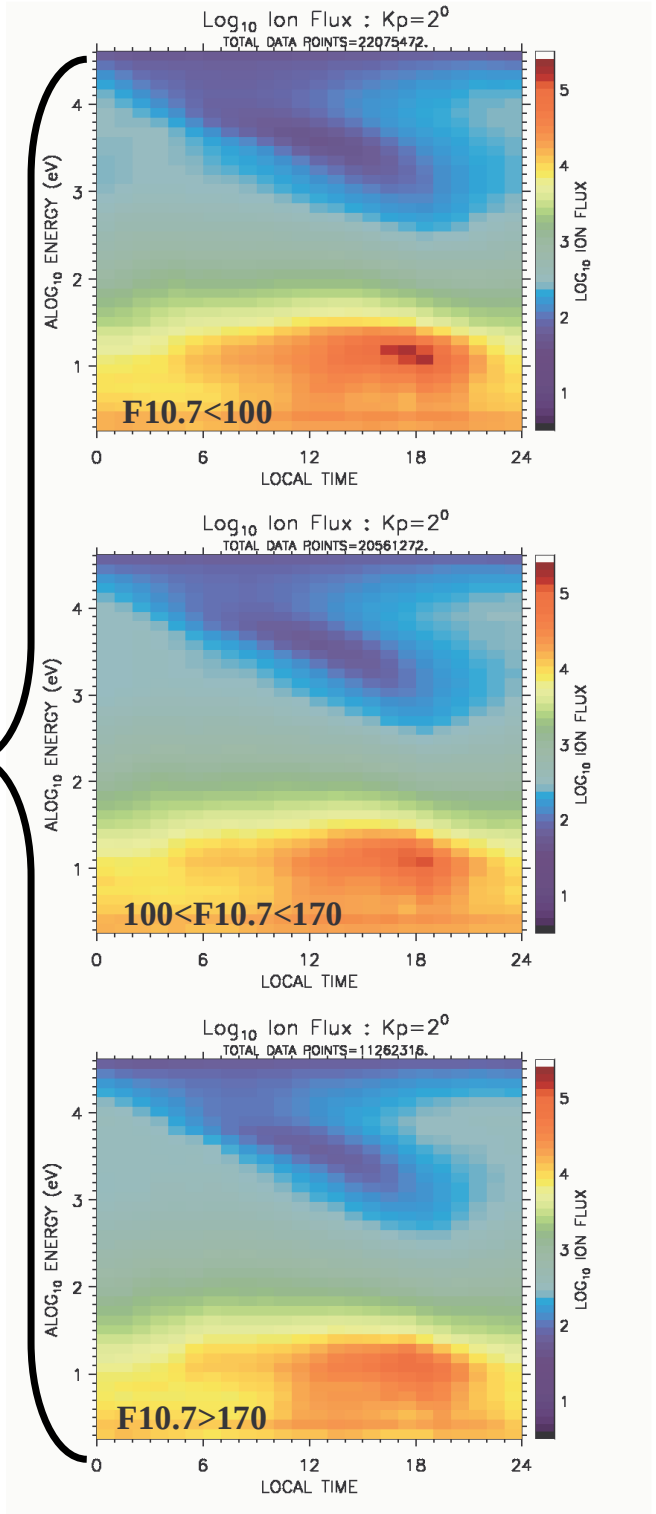
Given the large size of the LANL/MPA database, it is also possible to include a coarse solar-activity dependence, parameterized by F10.7.





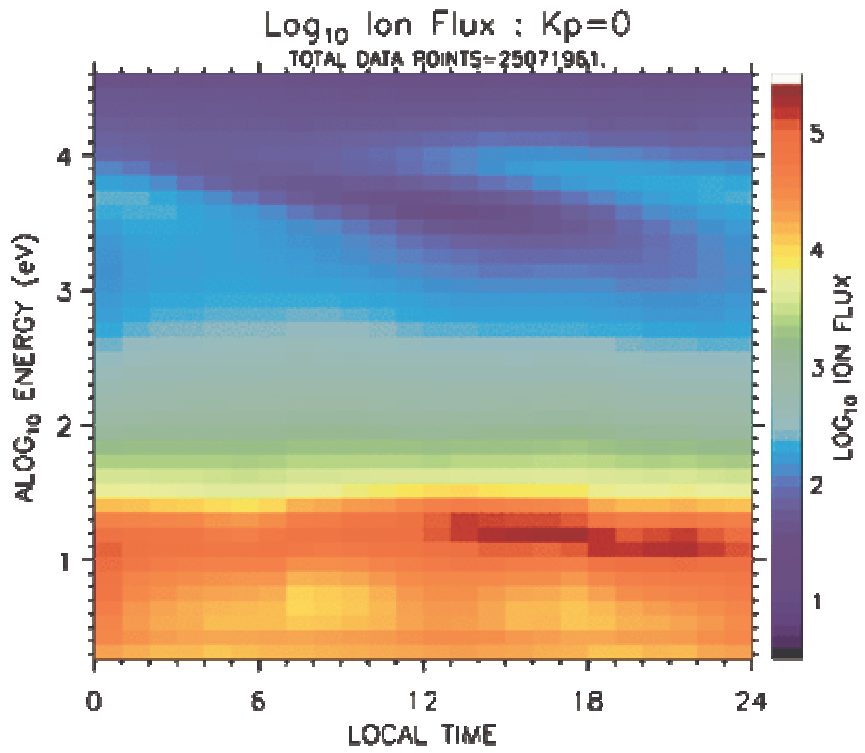
[after Thomsen et al., 2007]

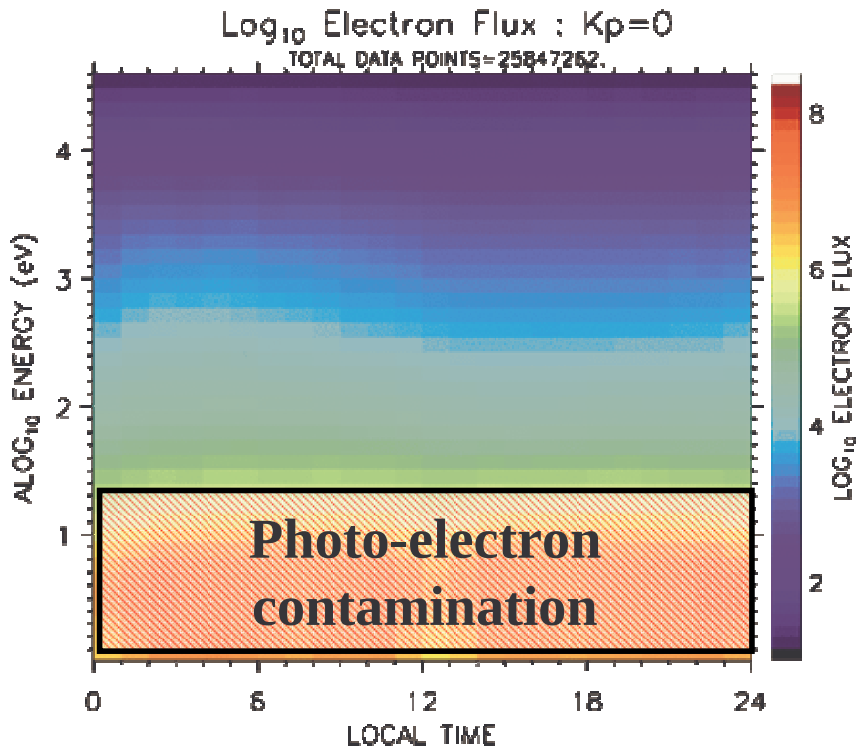
Up to factor of ~3 difference between mean flux from **low** to **high** solar activity



Model Description

The model describes the AVERAGE state of the ion and electron plasmas between ~1 eV and ~40 keV for all local times, and for all possible Kp values.





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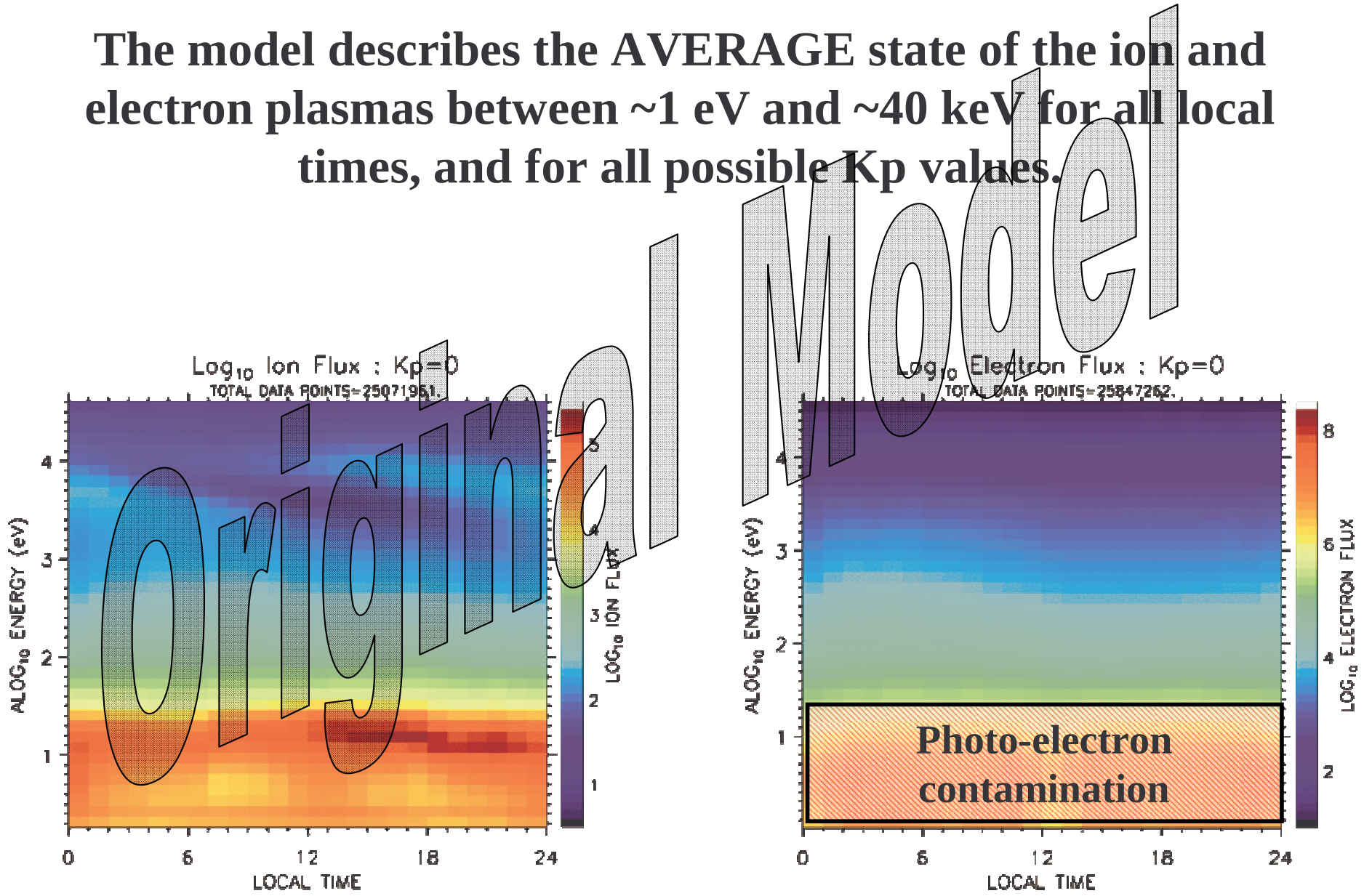
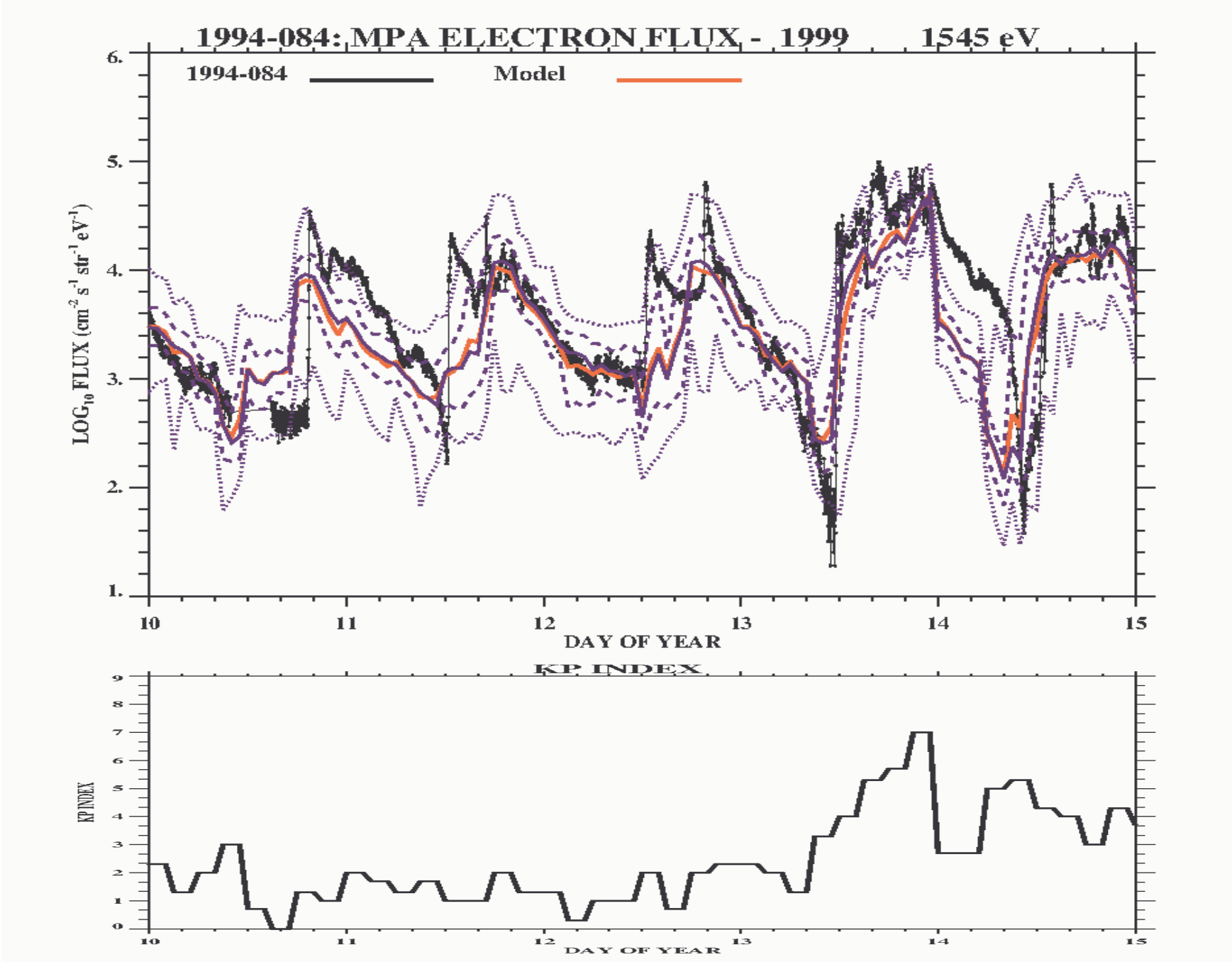
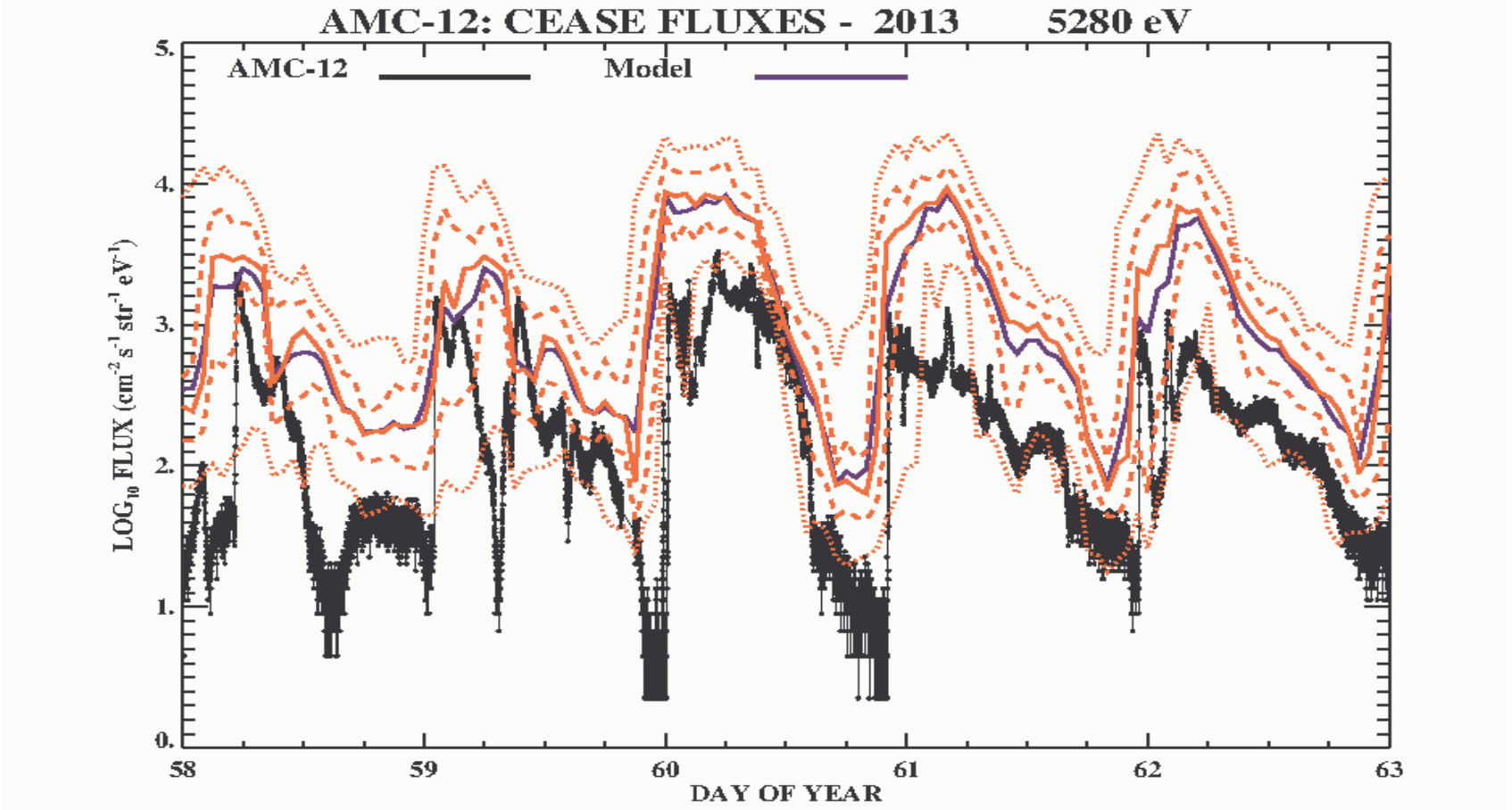
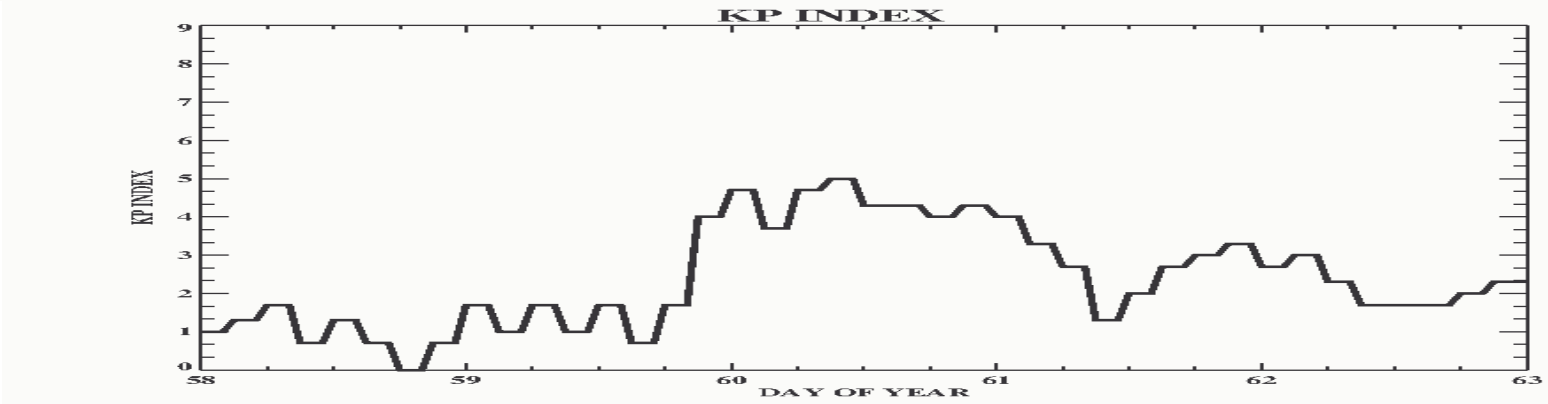


Model Verification and Testing



Model Verification and Testing

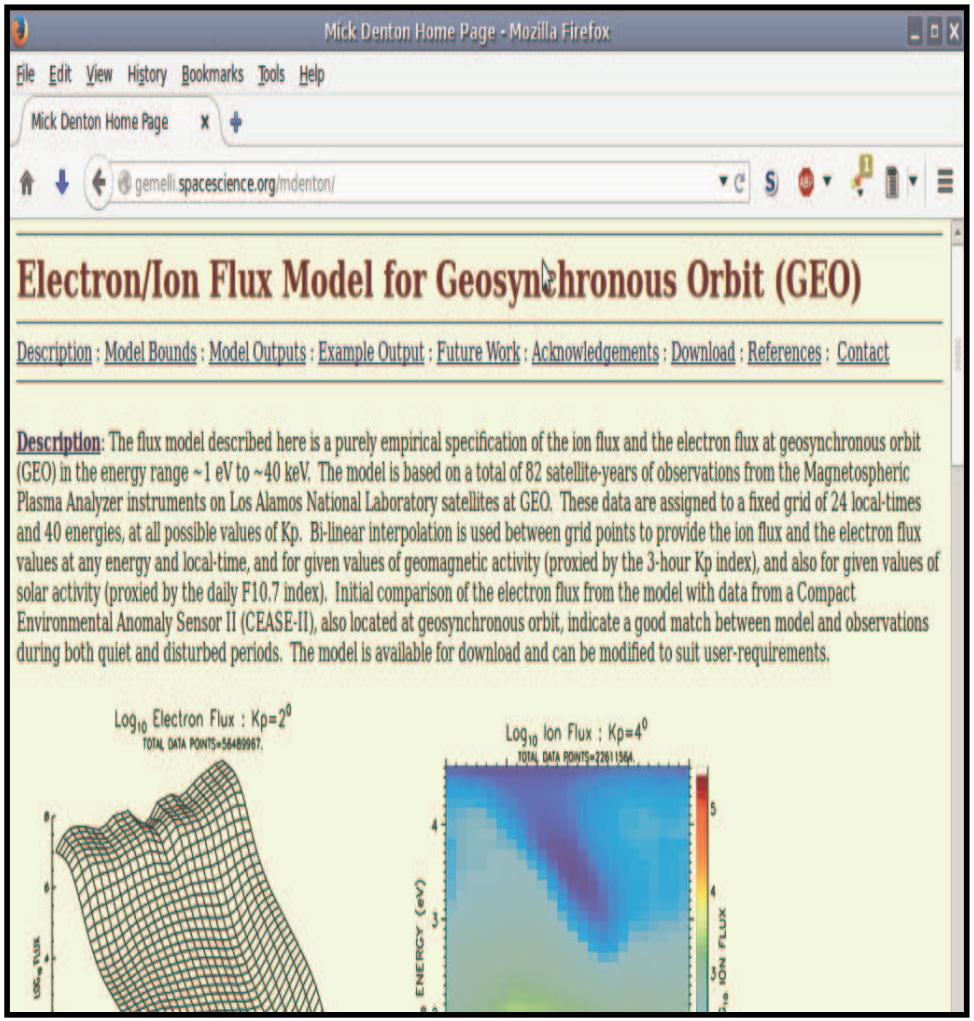


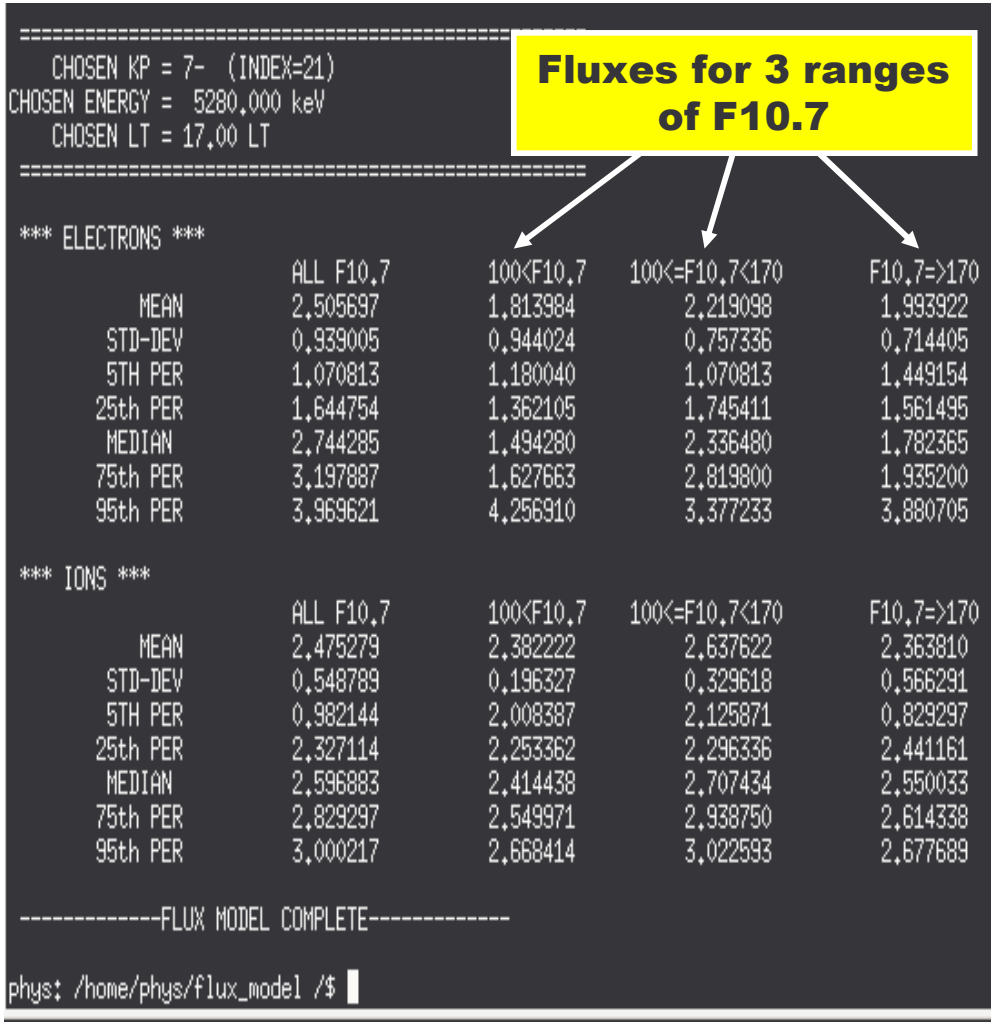


Where To Get It

You can download the model from: **http://gemelli.spacescience.org/mdenton/**

Denton, M. H., M. F. Thomsen, V. K. Jordanova, M. G. Henderson, J. E. Borovsky, J. S.Denton, D. Pitchford, D. P. Hartley, **An empirical model of electron and ion fluxes derived from observations at geosynchronous orbit**, ***Space Weather***, 13, doi:10.1002/2015SW001168, **2015**.





Model Verification and Testing

- Measured fluxes are (almost) always within envelope between 5th and 95th percentiles of the model predictions.
- This would certainly improve if on-orbit cross-calibration between satellites was carried out.
- The predicted fluxes from the model generally match observations very well, even when the model is driven by the Kp index alone.
- The predicted fluxes would likely improve further if we can derive a model that is based on parameters which describe the dynamics of the magnetosphere more completely.

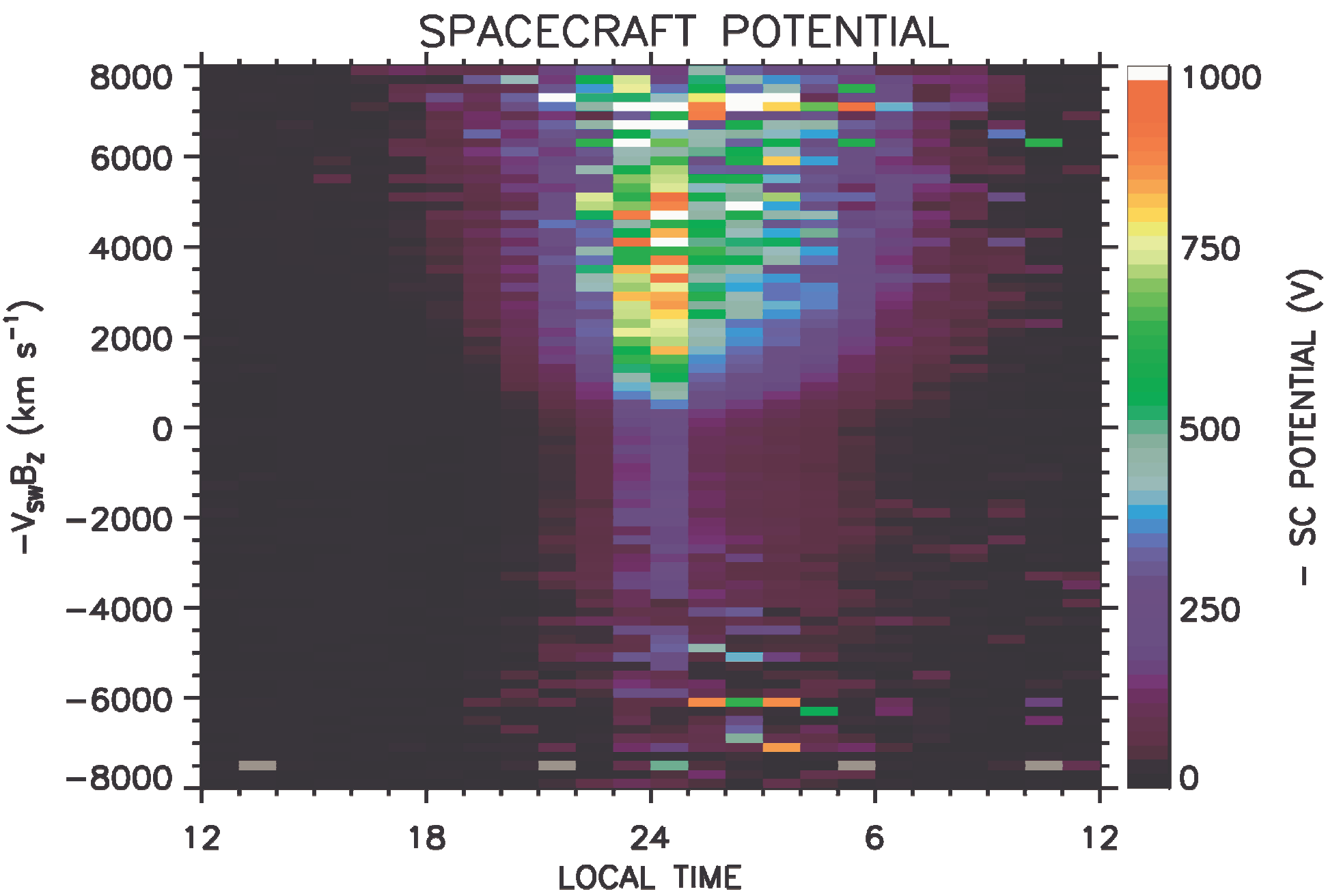
The New Model

How might we improve the '*weather forecast*'?

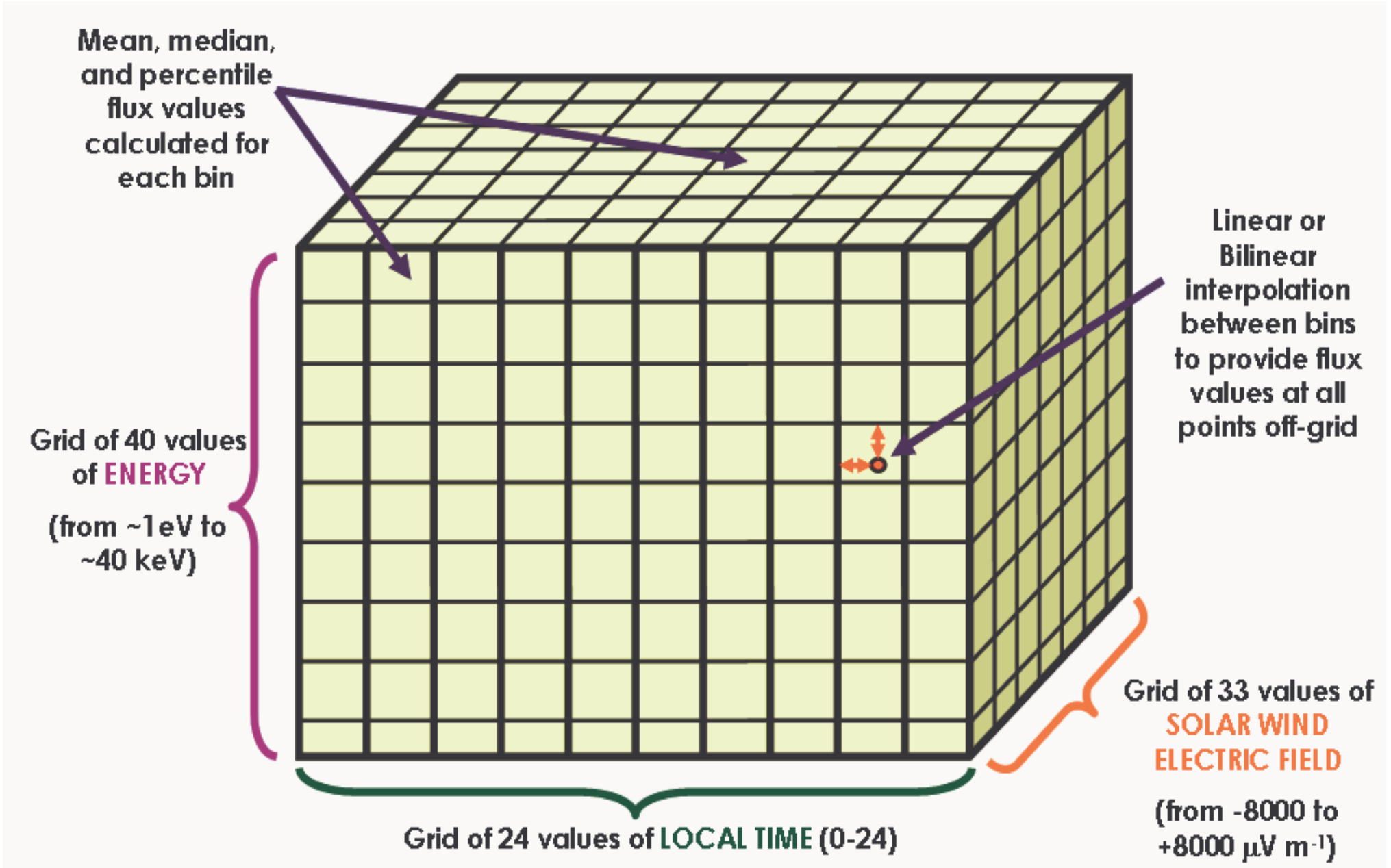
- **Use upstream solar wind electric field, $-v_{sw}B_z$ (where v_{sw} is the solar wind velocity and B_z is the z-component of the magnetic field in GSM coordinates).**

- **Ingest data from other satellite instruments (e.g. RBSP). This could extend the current model in energy and in spatial location.**

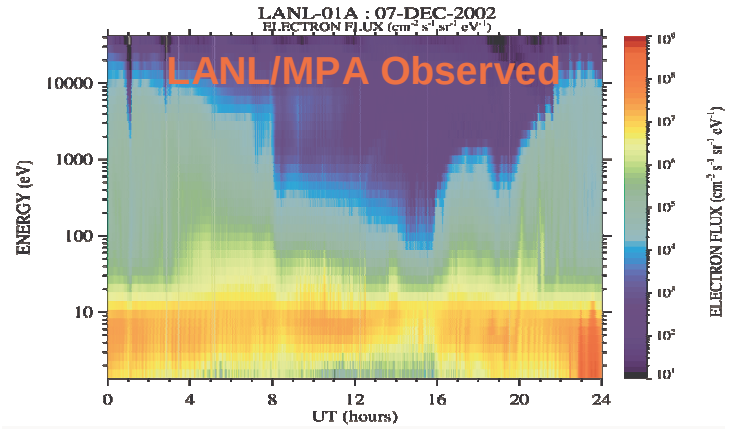
- **Drive the model with the 'new' solar-wind/magnetosphere coupling functions that have recently been developed.**

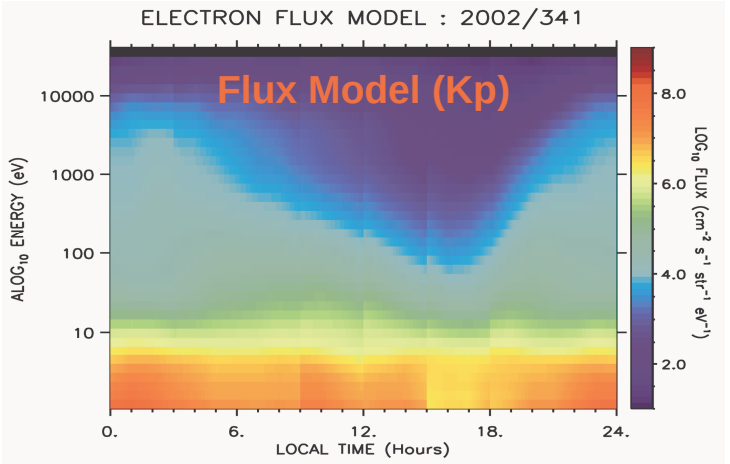

SPACECRAFT POTENTIAL
8000
6000
4000
2000
0
−2000
−4000
−6000
−8000
$-V_{sw}B_z$ (km s^{-1})
12
18
24
6
12
LOCAL TIME
1000
750
500
250
0
– SC POTENTIAL (V)

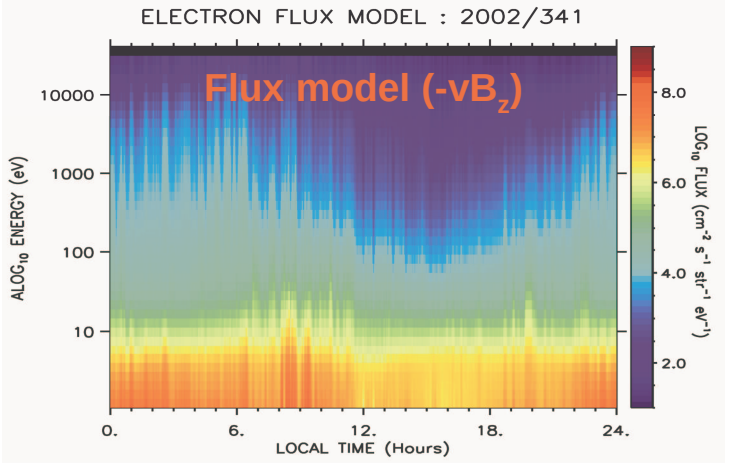
Binning Scheme for -vB_z Model



Results for -vB$_z$ Model







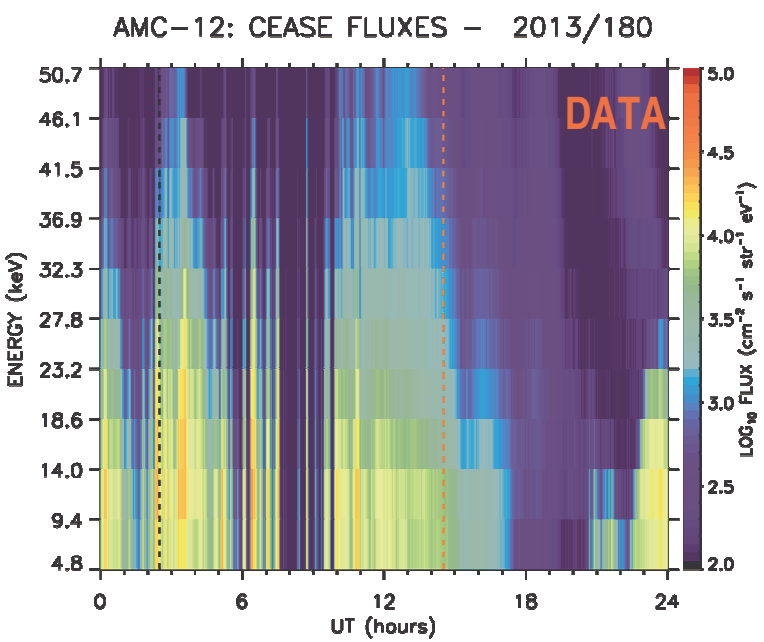
Results are compared between the Kp model and the new -vB$_z$ model

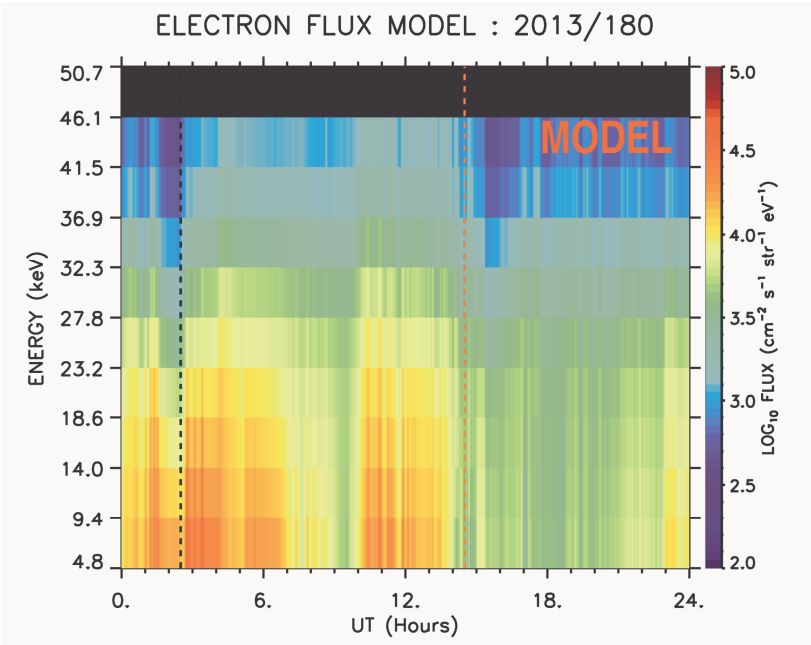
In this case, both models reproduce the broad features observations but do not replicate many of the observed features.

The Kp model has smooth variations but misses many rapid changes.

The -vB$_z$ model does replicate some of the small-scale structure. It also has the advantage of 1-hour predictivity allowing satellite operators

Results for -vB$_z$ Model





Using upstream solar wind, we can make predictions as to the flux environment for ANY satellite at GEO, ~1 hour in advance (DSCOVR / ACE data).

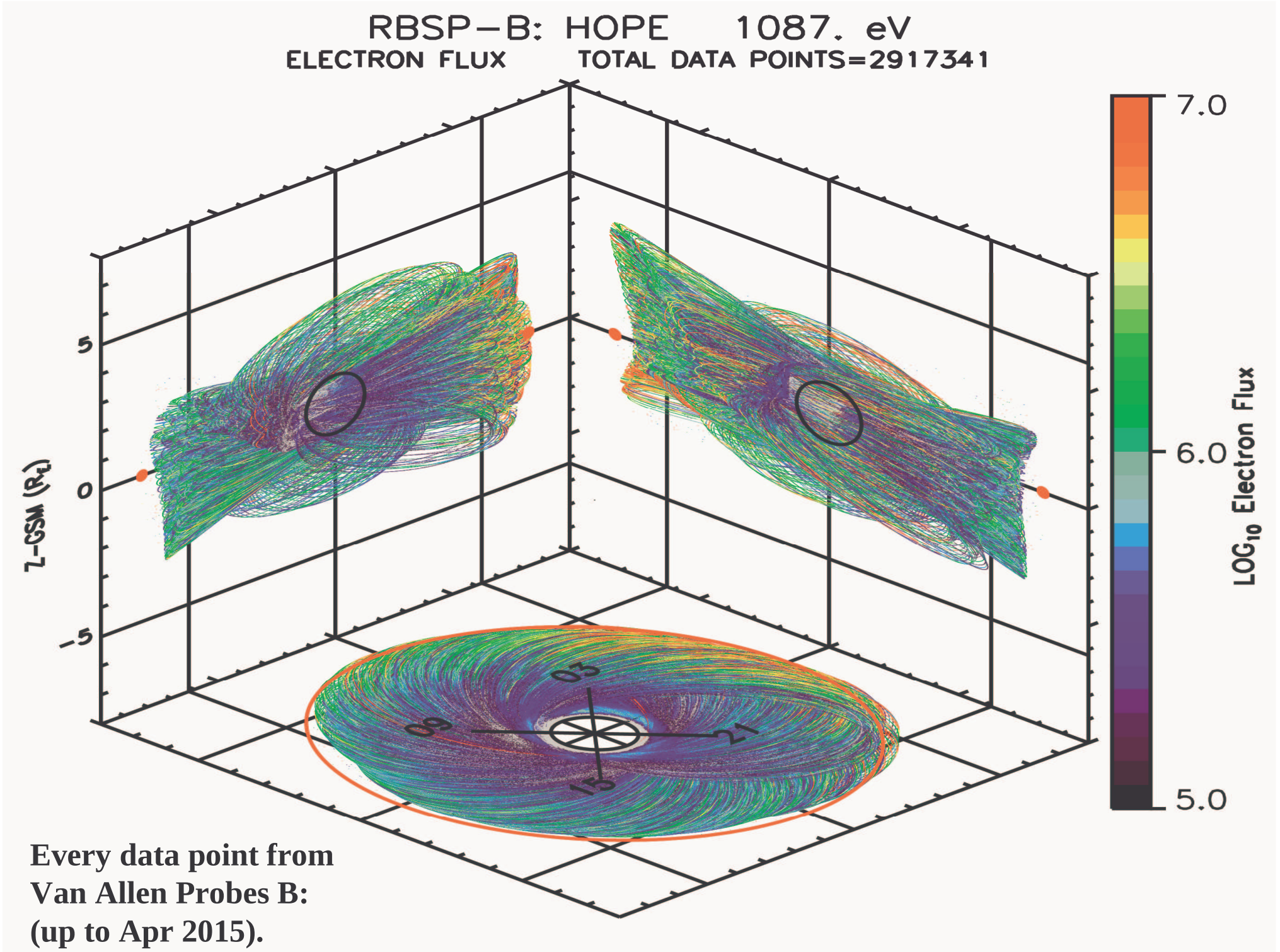
Here, the AMC-12 fluxes are ×15 Akin to on-orbit cross-calibration...

Otherwise the model flux predictions are a reasonable match to observations, although the model fluxes, derived from LANL/MPA, appear to have a much higher background flux than observed by AMC-12.

Model release will follow in next couple of months...

Summary

- We have developed a new empirical model of the flux environment at GEO.
- The model has been tested against independent data sets and the results are encouraging
- The model currently is driven by Kp or -vBz, but can be easily adapted to other parameters - next we will test coupling functions.
- We hope to continually expand the model to ingest other data from GEO (e.g. GOES, Van-Allen Probes, etc).
- The model is aimed at scientists, modelers, and spacecraft designers/operators, and is currently freely available.
- '*Weather forecasting*' led to both better forecasts and improved understanding of the physical causes of terrestrial weather.
- Similarly we hope for better physical understanding of the space environment and better forecasts.



Every data point from Van Allen Probes B: (up to Apr 2015).